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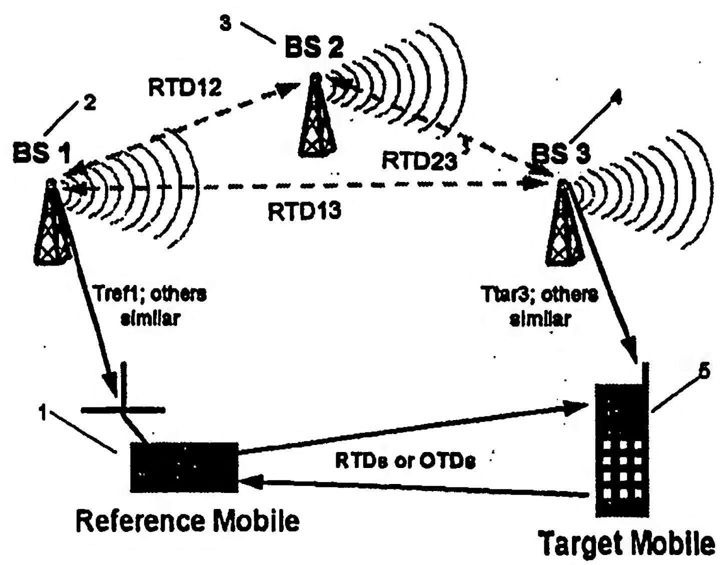
(57) Abstract



A digital cellular radio communication network, for example, a GSM or CDMA network, including a plurality of mobile stations; a number of base stations (BSs), each one of which is adapted to communicate with a number of mobile stations and has a known fixed geographic location in the network; and location means for determining the geographic location of a mobile station in the network. The location means includes at least one reference mobile station having a known geographic location in the network and which is adapted to receive signals broadcast by said base stations, and the received signals are used to determine the geographic location of a subscriber mobile station in the network. A mobile station includes means adapted to (a) identify, and measure the time of arrival of, the earliest arriving copy of a signal broadcast by a base station and received as a composite of plural copies, the time of arrival being measured relative to an internal time base of said mobile station, and (b) determine the relative timings of signals broadcast by a number of base stations. The relative timings of the signals are used to determine the geographic location of the mobile station in the network. The signals may be broadcast on a BCCH of each of the base stations, a BCCH signal conveying to a mobile station information concerning the broadcasting base station and the digital cellular radio communication network.

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LOCATION SYSTEM FOR DIGITAL MOBILE TELEPHONY

The invention relates to a digital cellular radio communication network, such as a GSM (Global System for Mobile Communication), or CDMA (Code Division Multiple Access), network and, in particular, to the determination of the geographic location of a mobile station within the coverage area of the network. The invention also relates to a location system, including a digital cellular radio communication network, for use in tracking a fleet of vehicles, each one of which includes a mobile station, and/or in a vehicle navigation system.

The principle of determining the position of a mobile radio-receiving apparatus by measuring time-of-flight differences between radio signals from several transmitters is well known, and a number of systems have been proposed and implemented. Most of the known systems rely on precise time synchronisation of the transmitters so that time-of-flight differences can be directly calculated. Knowing the geographical locations of the transmitters, particular values of these time differences identify a hyperbolic surface, in the space between each pair of transmitters being monitored, on which the radio-receiving apparatus must lie. Given three such hyperbolic surfaces, i.e. derived from three transmitters taken in pairs, the mobile radio-receiving apparatus must lie at the Intersection of the surfaces.

Location systems that use time-synchronised transmitters, for example, DECCA, OMEGA and LORAN-C, have been in widespread use since the 1940s.

It should be noted that it is only necessary for the actual time offsets, excluding any flight times to a receiver, (herein referred to as 'Real Time Difference', or 'RTD'), between the transmitters, to be known, not that the transmitters in fact transmit with zero time difference. Errors in position determination can be reduced by using more than three transmitters.

A related position-determining system has been proposed and demonstrated in our European Patent EP-B-0 303 371 in which it is not necessary for the RTD of the transmitters to be known, *a priori*.

It will be seen from Figure 1 of the accompanying drawings, which diagrammatically illustrates our earlier system, in the form of a block diagram, that the system uses a mobile station, 1, (hereinafter referred to as a 'reference mobile station') which has a known fixed geographic location in the system and which is adapted to monitor the signals broadcast by three transmitters, 2 to 4. These transmitters are used as references for determining the geographic location of a mobile station, 5, (hereinafter referred to as a 'target mobile station').

As illustrated in Figure 1, the target mobile station, 5, is adapted to monitor the same broadcast signals as the reference mobile station, 1. At some point in time, the target mobile station, 5, makes a short recording of each of the signals broadcast by the three transmitters, 2 to 4. The three recordings made by the target mobile station, 5, must be precisely spaced in time. The reference mobile station, 1, makes a similar set of recordings, almost simultaneously with the recordings made by the target mobile station, 5. It is important that the three recordings are made at precisely the same interval in the reference mobile station, 1, and the target mobile station, 5. Close synchronisation of the start time for the recordings reduces the amount of:

- computation needed to determine the geographic location of the target mobile station 5; and
- storage needed in the reference mobile station, 1, and the target mobile station 5

by reducing the lengths of the recordings that must be made at the reference mobile station, 1, but does not affect the accuracy of the determined geographic location and so is not critical.

A representation of the three recordings is communicated from the target mobile station, 5, to the reference mobile station, 1, where correlation techniques are used to determine the time offsets between the signals as received at the target mobile station, 5, and as received at the reference mobile station, 1. The recordings are long enough to ensure that the worst-case time offsets between reference and target recordings will still result in substantial overlap of the recordings. Since the geographic locations of the three transmitters, 2 to 4, and of the reference mobile station, 1, are known, the observed time of flight differences can be used to determine the location of the target mobile station 5 and the synchronisation offset between the reference mobile station

1 and the target mobile station 5, by solving the equations given in EP-B-0 303 371.

It will be seen from the foregoing description that the system of Figure 1 of the accompanying drawings compares two recordings of the 'live' signals broadcast by the transmitters, 2 to 4. The transmitters, 2 to 4, may, for example, be base stations (BSs) in a digital cellular radio communications network, such as a GSM, or CDMA, network. It should be noted that differences in the exact time when the recordings start can be eliminated in the subsequent position calculation.

The system of Figure 1 of the accompanying drawings has several disadvantages, namely:

- a reference mobile station is needed in order to capture a reference copy of the broadcast signals at a known location;
- substantial computing power is needed to perform the necessary correlations to determine the time offset between the signals, as seen at the reference mobile station, and the signals, as seen at the target mobile station;
- assuming that position determination is required with only a short time delay, a near-real-time communications link is needed to transfer the recordings made at the target mobile station to the reference mobile station for correlation each time it is required to determine the geographic location of a target mobile station;
- the bandwidth required for said communication link may be considerable, increasing the cost of said communication;
- the reference mobile station, in the system of Figure 1, has to perform recordings and correlations for all target mobile stations wishing to determine their geographic locations, at any point in time, thereby further increasing the computation capacity needed in the reference mobile station; and
- if the need for position information is, in fact, at the target mobile station, rather than some central location, a further real-time communications link is needed to transmit the result of a position determination back to the target mobile station, in a timely manner.

In a subsequent application (WO-A-97-11384) we show how this system may be applied to a GSM or other digital cellular network. Therein is disclosed a method by

which the effects of multipath propagation on the accuracy of the position determination can be ameliorated. In effect, the expected cross-correlation function between the signals received by the reference MS, 1, and the target MS, 5, is estimated from the auto-correlations of the signals received at the two MSs and this is fitted to the observed cross-correlation. The effect is to allow for the spectrum of delayed signals in such a fashion as to provide a better estimate of the undistorted time difference.

In yet another patent application (WO-A-97-30360), it is shown how the position of a mobile station in a GSM network can be obtained. However, in practice the largest source of error in the calculated position is likely to be due to multipath propagation between transmitter and receiver. In this application the output from the equaliser within a GSM handset is used to determine time offsets. This output is optimised to give the lowest bit error rate for signals received by the mobile station, and does not mitigate against the effects of multipath on the received signal for timing purposes.

In yet another application (WO-A-97-23785), there is disclosed a method by which the standard equaliser contained within every digital mobile telephone can be adapted to discriminate against multipath by using the estimate of the channel impulse response.

It is an object of the present invention to provide a digital cellular radio communication network, such as a GSM, or CDMA, network, which mitigates against several of the above-mentioned disadvantages of the known systems of Figure 1 of the accompanying drawings. This is effected by providing a system wherein signal structures are used which are designed to have good auto-correlation properties in TDMA broadcast channels, or CDMA pilots, conveying system information from each base station (BS) of the network, and wherein such signals are repeated at predictable/predetermined intervals in time that are identifiable from other information in the broadcast signal, for example, by frame numbering.

It is an object of another aspect of the present invention to combine the advantages of the readily identifiable signal structures designed to have good auto-correlation properties, e.g. the extended training sequences in GSM, with the method outlined above to discriminate against multipath propagation.

It is another object of the present invention to provide a location system, including a digital cellular radio communication network of the present invention, for use in tracking a fleet of vehicles, each one of which includes a mobile station, and/or in a vehicle navigation system.

According to a first aspect of the present invention, there is provided, a digital cellular radio communication network including a plurality of subscriber mobile stations; a number of base stations, each one of which is adapted to communicate with a number of mobile stations and has a known fixed geographic location in the network; and location means for determining the geographic location of a mobile station in the network, said location means including at least one reference mobile station having a known geographic location in the network and being adapted to receive signals broadcast by said base stations, said received signals being used to determine the geographic location of a subscriber mobile station in the network, characterised in that

a mobile station includes means for identifying and measuring the time of arrival of a signal broadcast by a base station, each broadcast signal received by said mobile station being a composite signal consisting of one or more copies of a signal transmitted by a respective base station, said copies being displaced in time relative to each other according to the relative lengths of the paths traversed by each copy between the respective base station and the mobile station, and said time of arrival being measured as the time of arrival of the earliest arriving copy forming said composite signal relative to an internal time base of said mobile station, and said means being arranged to determine the relative timings of signals broadcast by a number of base stations, and

said relative timings of said signals are used to determine the geographic location of said mobile station in the network.

Identifying, and measuring the time of arrival of, the earliest-arriving copy of said composite signal may be done as described later.

The signals transmitted in digital cellular telephone networks include parts which are transmitted at known intervals and which are readily identifiable and known in advance.

Preferably, the time of arrival of a signal received from a base station, relative to said internal time base, is identified and measured, in time or equivalent transformed space, by

auto-correlating a measured part of said signal;

constructing a template comprising a portion of the auto-correlation of an expected part of said signal and a portion of the auto-correlation of a part of the measured part of said signal;

cross-correlating the expected part of said received signal with the measured part of said received signal; and

measuring the offset at which the template best fits the cross-correlation as the time of arrival of the signal broadcast by a base station relative to said internal time base. The invention also includes a mobile station comprising means for carrying out the above method.

It is possible to carry out this process, equivalently, for example, in the Fourier transform domain, in which case the auto-correlation function becomes the power spectrum and the cross-correlation function becomes the cross-power spectrum.

The signal parts which are readily identifiable and known in advance, in the case of a GSM system may be, for example, the extended training sequence. In the case of a CDMA system the parts of the signal may be pilot spreading codes.

The signals may be broadcast on a Broadcast Control Channel (BCCH) of each of said base stations, a BCCH signal transmitted by a base station conveying to the mobile stations, with which said base station is adapted to communicate, information concerning said base station and the digital cellular radio communication network, and the handset may be adapted to determine the relative timings of the signals broadcast by a number of base stations using, for example, frame numbering and other identifying features of said BCCH signals.

The network may be either a GSM, or a CDMA, network, and the the relative timings of the signals broadcast by a number of base stations may be determined using, in the case of GSM, a training sequence in the TDMA frames, and, in the case of CDMA, pilot spreading codes.

The network may include evaluation means for evaluating said relative timings of said signals to determine the geographic location of said mobile station in the network, and transmission means for transmitting said relative timings from said mobile station to said evaluation means. The mobile station may include means adapted to receive, from said evaluation means, data concerning its geographic location in the network, and to store said data.

A mobile station (MS), the geographic position of which is being determined, may include means adapted to receive, from at least one external source, information on said relative timings and geographical locations of said base stations, and to store said information.

A mobile station (MS) may include location means adapted to determining the mobile station's geographic location in said network using said relative timings, in combination with base station timing and geographic location information.

The mobile station used to determine said relative timings may be a reference mobile station, and the reference mobile station may include calculation means adapted to calculate differences in bit and frame timing between transmissions from different base stations, in combination with information concerning said reference mobile station's geographic location and said base stations' geographic locations, said calculated data being used to determine the RTDs (Real Time Differences) of the base stations and thereby the geographic location of a subscriber mobile station.

The reference mobile station may include means adapted to determine, and predict, a rate of change of said timing differences between base stations. The reference mobile station may include transmission means for transmitting said calculated relative timings and rates of change to an external system for use in geographic position determination. The transmission means may be adapted to transmit base station position information to said external system.

The reference mobile station may have a known fixed geographic location in the network.

Alternatively, the geographic location of said reference mobile station in the network may be variable but determinable at any instant in time, for example, by using the signals of the Global Positioning System, GPS.

At least some of said base stations may each have a reference mobile station integral therewith.

The invention also includes a location system including a digital cellular radio communication network as outlined above. The location system may include a control centre for controlling operation of the system.

The location system may be adapted to determine the geographic location of any one of said mobile stations (MSs) in said network, in which said relative timings of base stations (BSs) used to determine said geographic locations are subject to variations at a rate approaching that of a signalling frame rate of signals transmitted by said base stations, in which said system includes a reference mobile station for each set of base stations used to determine said geographic locations, in which a mobile station, whose location is to be determined (herein referred to as a 'target mobile station'), is assigned a set of base stations by said control centre, said target mobile station being adapted to measure relative timings of signals transmitted by said assigned set of base stations, at times given in terms of the frame number at an agreed base station, in which at least one reference mobile station, associated with said assigned set of base stations, is adapted to measure relative timings of said signals transmitted by said assigned set of base stations, in which said target mobile station and said reference mobile station are adapted to transmit said measured timings to said control centre, in which said control centre is adapted to compare said time information from said target mobile station and said reference mobile station to determine a time difference, and in which said control centre is adapted to calculate the geographic location of said target mobile station using said time difference information, and information, known to said control centre, concerning the geographic locations of said assigned set of base stations and said reference mobile station, said calculation being effected using conventional hyperbolic geometry equations. The control centre may be adapted to change the set of base stations, assigned to a mobile station, as said mobile station travels within the coverage area of the digital cellular radio communication network. The control centre may be adapted to co-ordinate information

concerning timing measurements from at least some of said reference mobile stations. The location system may be adapted to track a fleet of vehicles, each one of which includes a mobile station (MS).

The invention also includes a vehicle navigation system adapted to enable vehicles to determine their geographic locations, in which said navigation system includes a location system as outlined above, and in which each of said vehicles includes a mobile station (target mobile station). The system may include a reference mobile station for each set of base stations used to determine said geographic locations, in which rates of change of relative timings between base stations are sufficiently stable to enable said relative timings to be accurately predicted, for relatively long periods of time, according to a model shared between said reference and target mobile stations, in which said control centre is adapted to collect relative timing information and rate of change information measured by each of said reference mobile stations for respective sets of base stations, in which said control centre is adapted to distribute measurement information collected from said reference mobile stations to target mobile stations, travelling within the coverage area of said digital cellular radio communication network, said information distribution being such that each of said target mobile stations has sufficiently accurate information concerning relative timings of base stations with which it can communicate in any given geographic location of said network, in which a target mobile station is adapted to measure relative timings of signals transmitted by a set of base stations in its current location, and to determine its geographic location using said measurements, together with said information distributed by said control centre and information concerning geographic locations of said set of base stations. The control centre may be adapted to provide, to said target mobile station, information concerning geographic locations of said set of base stations. The target mobile station may include a database in which said information concerning geographic locations of said set of base stations is stored.

The foregoing and other features of the present invention will be better understood from the following description with reference to the accompanying drawings, in which:

Figure 1 diagrammatically illustrates, in the form of a block diagram, a known system for determining the geographic location of a mobile receiving apparatus;

Figure 2 diagrammatically illustrates, in the form of a block diagram, a digital cellular radio communication network of the present invention;

Figures 3A-D illustrate estimated and measured auto- and cross-correlation functions of signals in the system as will be described below; and

Figure 4 is a diagrammatic illustration of a mobile handset for a digital cellular radio network embodying the invention.

The following description of the present invention, which is given by way of example only, specifically relates to the determination of the geographic location of a mobile station of a GSM digital cellular radio communication network. It will, however, be readily understood by persons skilled in the art that the present invention could be used in other digital cellular radio communication systems, for example, a CDMA digital cellular radio communication network.

It will be seen from Figure 2 of the accompanying drawings, which diagrammatically illustrates, in the form of a block diagram, a GSM-type digital cellular radio communication network, that the reference mobile station, target mobile station and base stations have been given the same references as the corresponding equipments in Figure 1 of the accompanying drawings.

In this example of a GSM digital cellular radio communication network according to the present invention, each base station (BS) of the network broadcasts signals on a Broadcast Control Channel (BCCH), to those of the network's mobile stations (MSs) within its coverage area, which convey information concerning the digital cellular system and the broadcasting base station.

The BCCH radiated by a base station (BS) also includes signals to assist the mobile stations (MSs), within its coverage range, in acquiring synchronisation to the radiating base station, when a mobile station is first turned on, or when the mobile station re-enters the coverage area of the radiating base station, after a temporary loss of signal. The BCCH signals include features designed to enable a mobile station to acquire and maintain bit synchronisation with the base station concerned; these

features are transmitted at precise and regular intervals in the TDMA structure of the GSM network and are readily identifiable.

It will be readily understood by persons skilled in the art that the BCCH signals can be used to establish, with high accuracy, the bit and frame timing of any particular base station, as received at a mobile station. In normal signalling conditions, the accuracy of the bit and frame timing information, established from the BCCH signals, is typically a small fraction of a bit period.

Unless a mobile station has line of sight to a base station, the received signal is very likely to be a composite signal consisting of one, or more, copies of the signal transmitted by the base station, the copies being displaced in time, relative to each other, according to the relative lengths of the paths taken by each copy of the signal between the receiving mobile station and the transmitting base station. The earliest-arriving copy of the signal will be that copy which has taken the shortest path between the base station and mobile station; the shortest path need not necessarily be a direct path between the base station and mobile station. The path error in the shortest received path will be the greatest single error source in most of the position measurements effected using the digital cellular radio communication network of the present invention.

Measuring the time of arrival of the earliest to arrive of the copies of such a multipath composite signal relative to an internal time base of the mobile station enables this error to be minimized. This example of the present invention makes use of readily identifiable signal structures designed to have good auto-correlation properties, e.g. the extended training sequences in a GSM digital cellular network, and is illustrated in Figures 3A to 3D. The auto-correlation function of the extended training sequence in a GSM signal (illustrated in Figure 3A) is well known. The left hand side of this (corresponding to the negative time axis) is used as the left hand side of an estimated cross-correlation function (illustrated in Figure 3C) of the received signals and the expected extended training sequence. The right hand side of the auto-correlation function of the measured extended training sequence (illustrated in Figure 3B and corresponding to the positive time axis) is used as the right hand side of the estimated cross-correlation function. The received signals are cross-correlated with the expected extended training sequence and the resulting measured cross-correlation

function (illustrated in Figure 3D) compared with the estimated cross-correlation function (Figure 3C) to find the timing offset.

Figure 4 is a simplified diagram of a mobile station comprising a conventional digital cellular radio handset adapted to operate in accordance with the invention. The handset 5 includes an antenna 51 which provides a signal to a receiver 52, from which the received signal is passed to a digital signal processor (DSP) 53. The digital signal processor 53 has an associated RAM 54 and a ROM 55 or similar for containing software used by the DSP 53. A conventional microprocessor 56 receives signals processed by the DSP and also has associated RAM 57 and ROM or similar 58 for containing operating software. The other normal components of a cellular telephone handset, eg battery, keypad, LCD screen etc. are not shown as they are not germane to the present invention. In use in accordance with the invention, the DSP 53 and associated RAM 54, operating under the control of a modified program stored in ROM 55 operate to carry out the required signal measurements and the microprocessor 56 and associated RAM 57 operate to measure the timing offsets under the control of a modified program stored in the ROM 58.

An alternative method is to make use of the fact that a GSM mobile station (MS) includes a mechanism, e.g. an equaliser with a channel sounder, for determining which copy of a composite signal, resulting from a signal transmitted by a base station, the mobile station should select and use in order to achieve the lowest bit error rate in the demodulated signal. A modified GSM mobile station may be used which includes equalising means (including a channel sounder) adapted to identify, and measure the time of arrival of, a signal transmitted by a base station. In practice, the signal which is identified and measured by the equalising mechanism will be the earliest-arriving copy of the composite signal transmitted by a base station. An equaliser, operating in this mode, does not need to demodulate the signal but merely needs to establish its timing, and may, therefore, be able to operate at lower received signal levels than would normally be required by an equaliser to effect reliable demodulation of the signal.

Such a mobile station may be a reference mobile station (MS) and/or a target mobile station (MS), i.e. a mobile station whose geographic location in the coverage area of the network is to be determined.

With a CDMA network, such as IS 95, the identification of the times of arrival of the signals could be performed by an equalising means, in the form of the CDMA searcher element in the mobile station.

It will be seen from Figure 2 that the reference mobile station, 1, and the target mobile station, 5, of the GSM network are each adapted to communicate with the network's base stations (BSs), 2 to 4, and that the reference mobile station, 1, and target mobile station, 5, are adapted to communicate with each other, probably by the GSM network. The reference mobile station, 1, and target mobile station, 5, each include means, e.g. an equaliser mechanism, as outlined in a preceding paragraph. Furthermore, the reference mobile station, 1, has a known geographic location in the coverage area of the network. In practice, the reference mobile station, 1, would normally have a known fixed geographic location in the network, but may have a geographic location which is variable but determinable at any instant in time, for example, by GPS. Alternatively, at least some of the network's base stations may each have a reference mobile station integral therewith, i.e. formed as an integral part of a base station and thereby eliminating the need for a separate unit. In practice, it may be advantageous/cost effective for each base station in the network to have a reference mobile station formed integral therewith, and for any one, or more, of the integral reference mobile stations to be activated as, and when required, by the network operator and/or a central control unit.

In operation, the reference mobile station, 1, receives signal transmissions from the three base stations (BSs), 2 to 4, and is adapted to calculated RTDs (Real Time Differences) between the base station signal transmissions using, for example, information concerning:

- the known geographic locations of the base station, 2 to 4, in the network;
- the known geographic location of the reference mobile station 1, in the network; and
- measured time difference between the times of arrival of the signal transmissions at the reference mobile station 1.

The reference mobile station, 1, may, in accordance with the present invention, also be adapted to determine the rate of change of the RTDs.

The target mobile station, 5, receives the same set of signal transmissions as the reference mobile station, 1, from the base stations, 2 to 4, and is adapted to determine OTDs (Observed Time Differences) between the set of signal transmissions. The OTDs and RTDs are then used, in combination with the information concerning geographic locations of the base stations (BSs), 2 to 4, to determine the geographic location of the target mobile station, 5, in the network using conventional hyperbolic geometry calculations.

As is diagrammatically illustrated in Figure 2 of the drawings, the RTDs, together with rate of change information, if available, are transmitted to the target mobile station, 5, by the reference mobile station, 1, or the OTDs are transmitted by the target mobile station, 5, to the reference mobile station, 1, after which the two sets of time differences are combined with knowledge of the geographic locations of the base stations (BSs), 2 to 4, to calculate the position of the target mobile using the conventional hyperbolic equations. In other words, the RTDs either alone, or in combination with the rate of change information, are transmitted to the target mobile station, 5, for use, in combination with the OTDs and the information concerning the geographic locations of the three base stations, 2 to 4, to determine the geographic location of the target mobile station, 1. Alternatively, the OTDs are transmitted to the target mobile station, 1, for use in combination with the RTDs either alone, or in combination with the rate of change information, and the information concerning the geographic locations of the three base stations, 2 to 4, to determine the geographic location of the target mobile station, 1.

It will be seen from the foregoing description of the present invention that rather than finding the time differences between the times of flight from the base stations (transmitters) to the two mobile stations, as in our earlier system, the present invention determines the RTDs between base station transmissions so that the standard DECCA-style, or LORAN-style, hyperbolic calculation can be used.

Fundamental to all implementations of the present invention is the use of a reference mobile station, at a precisely-known geographical location, to determine the relative bit and frame timings of a set of base stations. If these relative timings do not change, the reference mobile need not be permanently present, i.e. the relative timings

can be determined once and for all in an initial survey. However, if these relative timings do change for any reason (the usual case), the reference mobile station will need to be present to monitor the relative timings and update the information on such timings at a suitable rate. This rate will depend, among other things, on the frequency of network reconfigurations and the relative frequency stability of the base stations. The frequency with which updates need to be transmitted can be reduced by monitoring the rate of change of the relative timings and transmitting this information, along with the timings, at a specified start time.

Thus, the reference mobile station, 1, of a digital cellular radio communication network of the present invention, may be adapted to initially establish relative time differences for the three base stations, 2 to 4, and to thereafter update the relative timing information at predetermined intervals of time, or when a change in the time difference information is detected, whichever is the earlier. In which case, the reference mobile station, 1, includes monitoring means adapted to monitor a rate of change of the relative timings and to transmit, at regular intervals of time, information on the rate of change of the relative timings, together with the relative timings information.

It will be seen from the foregoing description of the present invention that the equaliser used by a mobile station may be provided with an alternative operating mode in which it identifies the earliest-arriving copy of the composite signal transmitted by a base station and measures the time of arrival of that copy relative to a suitable internal time base. As stated above, an equaliser, operating in this mode, does not need to demodulate the signal but merely needs to establish its timing, and may, therefore, be able to operate at lower received signal levels than would normally be required by an equaliser to effect reliable demodulation of the signal.

Thus, the mobile station of the present invention has the ability, using the alternative equaliser mode, to determine the relative timing of the signals from several base station BCCHs to a suitable/reasonable accuracy, taking account of frame numbering and other identifying features of the signal, particularly including (in the case of GSM), the training sequences in the TDMA frames. The mobile may be provided with transmission means to transmit these relative timings to some other point whether remote, or local, for evaluation.

It will be directly evident to a person skilled in art that a target mobile station of a digital cellular radio communication network of the present invention, i.e. as described in preceding paragraphs, may include:

- means for receiving a computed position result from an external source; and
- means for receiving information on relative timing and geographical locations of base stations from an external source, or sources, whether remote, or local;

either one, or both, of which may typically be provided as part of the normal communications functions of the mobile station.

A target mobile station may also include means for using base station timing and position information, together with locally measured relative timings, to compute its own position.

It will also be directly evident to a person skilled in art that a reference mobile station of a digital cellular radio communication network of the present invention, i.e. as described in preceding paragraphs, may include:

- means for using the relative timings measured between transmissions from different base stations, together with knowledge of the geographical locations of the base stations and knowledge of its own geographical location, to calculate the actual differences in bit and frame timing between transmissions from different base stations, as if observed at the actual base stations by precisely synchronised observers;
- means for determining and predicting the rate of change of the timing differences between base stations;
- means for transmitting the calculated relative timings and rates of change to external systems whether remote, or local, for use in determining the geographic location of a target mobile station; and
- means for transmitting base station position information to external systems for use in position determination.

A basic application of the digital cellular radio communication network of the present invention is in a location system adapted to determine the geographic locations

of any one of a number of mobile stations in the network. The location system of the present invention may, however, be used in a number of applications, for example, to track/monitor a fleet of vehicles, each one of which includes a mobile station (a target mobile station). Alternatively, the location system may form part of a vehicle navigation system, in which a vehicle, having a mobile station (target mobile station) located therein, wishes to determine its own location whilst travelling within the coverage area of the digital cellular radio communication system.

A location system for tracking/monitoring a fleet of vehicles, may be a relatively low cost application of the present invention in which a central site, or control centre, wishes to know the locations of any one of a number of vehicles, for example, a fleet of taxis, as they travel within the coverage area of the digital cellular radio communication network.

With this application of the location system of the present invention, it will be assumed, by way of example, that the relative timings of the base stations (BSs), used to determine the geographic locations of the vehicles, are subject to variations at a rate approaching that of a signalling frame rate of the signals transmitted by the base stations. This implies that it will be necessary to provide a reference mobile station for each set of base stations used to determine the geographic locations. Thus, in operation, a vehicle (target mobile station), whose geographic location is to be determined, is assigned a set of base stations (BSs), for example, by the control centre, and the vehicle's mobile station is adapted, in a manner as previously outlined, to measure the relative timings of the assigned set of base stations, at times given in terms of the frame number at an agreed base station, either periodically, or on demand. A reference mobile station, associated with the assigned set of base stations is adapted, in a manner as previously outlined, to measure the related timings of the signals transmitted by the same set of base stations as the target mobile station (vehicle). The measured timing information is transmitted by the reference mobile station and the target mobile station to the control centre. The control centre is adapted to compare the timing information from the target mobile station with the timing information from the reference mobile station, i.e. timing information from the same set of base stations in the same frame numbers, as received by the reference mobile station, to determine a time difference. The control centre then calculates the geographic location of the vehicle (target mobile station) using the time difference

information, and information, known to the control centre, concerning the geographic locations of the assigned set of base stations and the reference mobile station. The calculation is made using conventional hyperbolic geometry calculations.

With the location systems of the present invention, in which the reference mobile stations are co-ordinated by a control centre, it may only be necessary for the signals broadcast by at least two base stations to be measured by a reference mobile station in order to fix the geographic location of a target mobile station.

In practice, the set of base stations assigned to a vehicle will be a subset of those base stations the transmitted signals of which the vehicle's mobile station can measure. The control centre is adapted to change the set of base stations, assigned to a vehicle (target mobile station), as the vehicle travels within the coverage area of the digital cellular radio communication network. In other words, a set of base stations to be used to fix the position of a vehicle would typically be updated from the control centre, as the vehicle travels around.

The set of base stations, the signal transmissions of which any given reference mobile station can measure will not, in general, be a superset of those base stations the signal transmissions of which a specific target mobile (vehicle) can measure. There is, therefore, a need for the control centre to be able to co-ordinate measurements from some, or all, of the reference mobile stations.

It will be seen from the foregoing description of the vehicle location system that, in contrast to our earlier system, it is not necessary to transmit any representations of the received signals for correlation; the time differences are measured directly in the target mobile stations, and only this information is sent to the control centre, thereby greatly reducing the required communication bandwidth.

A vehicle navigation system in which each vehicle includes a mobile station (target mobile station) to enable it to determine its geographic locations, is a more sophisticated application of a location system of the present invention. With this system it will be assumed, by way of example, that the rates of change of relative timings between base stations (BSs) are sufficiently stable to enable the relative timings to be accurately predicted, for relatively long periods of time, according to a

model shared between a reference mobile station and a target mobile station, i.e. located in the vehicle wishing to determine its geographical location. With this system which includes a reference mobile station for each set of base stations used to determine the geographic locations, the control centre is adapted to:

- collect relative timing information and rate of change information measured by each of said reference mobile stations for respective sets of base stations; and
- distribute measurement information collected from the reference mobile stations to target mobile stations, travelling within the coverage area of the digital cellular radio communication network.

The distributed information is such that each of the target mobile stations (vehicles) has sufficiently accurate information concerning relative timings of base stations (BSs) with which it can communicate in any given geographic location of said network.

When a vehicle wishes to determine its geographic location, the vehicle's target mobile station measures the relative timings of the signals transmitted by a set of base stations (BSs) in its current location (not typically congruent with the set of base stations it may use for communication), and determines its geographic location using the relative timing measurements, together with the rate of change information distributed by the control centre and information concerning the geographic locations of the set of base stations (BSs).

The control centre of the vehicle navigation system may be adapted to provide, to the target mobile station, information concerning geographic locations of said set of base stations (BSs), or the target mobile station may include a database in which the information concerning the geographic locations of the set of base stations (BSs) may be stored.

It will be seen from the foregoing description of specific embodiments of the present invention that the location system, according to the invention, has the following characteristics and/or advantages over known systems for determining the geographic location of mobile apparatus:

- a reference mobile station is needed to capture a reference copy of the signals broadcast by a set of base stations at known locations; however, this can be very similar to the target mobile station - usually needs to update the timing information only infrequently, and so is low cost;
- correlations between two live signal recordings, as proposed in our earlier system, are no longer needed to determine the time-of-flight differences, hence reducing the required computing capacity of the system;
- the amount of data required to be transferred between the reference and target mobile stations is relatively small and, in some modes of operation of the present invention, the transfer from the reference mobile station to the target mobile station is infrequent, thereby reducing the cost of operation of the location system of the present invention;
- the reference mobile stations have to perform a set of timing and rate of change measurements that is common to all target mobile stations, further reducing the computation capacity needed in the reference mobile station; and
- if the need for position knowledge is in fact at the target mobile station, rather than at some central location, the target mobile station may conveniently carry out the position determination itself, based on an infrequent update of the base station timing information.

CLAIMS

1. A digital cellular radio communication network including a plurality of subscriber mobile stations (5); a number of base stations (2,3), each one of which is adapted to communicate with a number of mobile stations and has a known fixed geographic location in the network; and location means for determining the geographic location of a mobile station in the network, said location means including at least one reference mobile station (1) having a known geographic location in the network and being adapted to receive signals broadcast by said base stations (2,3), said received signals being used to determine the geographic location of a subscriber mobile station (5) in the network, characterised in that

a mobile station (5) includes means for identifying and measuring the time of arrival of a signal broadcast by a base station (2,3), each broadcast signal received by said mobile station being a composite signal consisting of one or more copies of a signal transmitted by a respective base station, said copies being displaced in time relative to each other according to the relative lengths of the paths traversed by each copy between the respective base station and the mobile station, and said time of arrival being measured as the time of arrival of the earliest arriving copy forming said composite signal relative to an internal time base of said mobile station, and said means being arranged to determine the relative timings of signals broadcast by a number of base stations, and

said relative timings of said signals are used to determine the geographic location of said mobile station in the network using conventional hyperbolic geometry.

2. A network according to claim 1, wherein the transmitted signals identified and measured comprise parts which are transmitted at known intervals and which are readily identifiable and known in advance.

3. A network according to claim 2, wherein said means for identifying and measuring the time of arrival of a signal received from a base station, relative to said internal time base, in time or equivalent transformed space, includes

means for auto-correlating a measured part of said signal;

means for constructing a template comprising a portion of the auto-correlation of an expected part of said signal and a portion of the auto-correlation of a part of the measured part of said signal;

means for cross-correlating the expected part of said received signal with the measured part of said received signal; and

means for measuring the offset at which the template best fits the cross-correlation as the time of arrival of the signal broadcast by a base station relative to said internal time base.

4. A network according to claim 2 or claim 3, wherein said network is a GSM network, and said part of said signal comprises an extended training sequence.

5. A network according to claim 2 or claim 3, wherein said network is a CDMA network, and said part of said signal comprises a pilot spreading code.

6. A network according to any of claims 2 to 5, wherein said means for constructing a template comprises means for combining a portion of the auto-correlation of an expected part of said signal corresponding to offset times before that of the central peak of said signal with a portion of the auto-correlation of a part of the measured part of said signal corresponding to offset times after that of the central peak.

7. A network according to claim 1, wherein said means for identifying and measuring the time of arrival of a signal broadcast by a base station (2,3) comprises an equaliser adapted for same.

8. A network as claimed in any of claims 1 to 7, in which said signals are broadcast on a Broadcast Control Channel (BCCH) of each of said base stations, and in which a BCCH signal transmitted by a base station conveys to the mobile stations, with which said base station is adapted to communicate, information concerning said base station and the digital cellular radio communication network, and in which said equalising means are adapted to determine the relative timings of the signals broadcast by a number of base stations using frame numbering and other identifying features of said BCCH signals.

9. A network as claimed in any preceding claim, in which said network includes evaluation means for evaluating said relative timings of said signals to determine the

geographic location of said mobile station in the network, and transmission means for transmitting said relative timings from said mobile station to said evaluation means.

10. A network as claimed in claim 9, in which said mobile station includes means adapted to receive, from said evaluation means, data conceming its geographic location in the network, and to store said data.

11. A network as claimed in any preceding claim, in which a mobile station, the geographic position of which is being determined, includes means adapted to receive, from at least one external source, information on said relative timings and geographical locations of said base stations, and to store said information.

12. A network as claimed in claim 1 or any of claims 7 to 11 when dependent thereon, in which a mobile station includes location means adapted to determining the mobile station's geographic location in said network using said relative timings, determined by the mobile station's equalising means, in combination with base station timing and geographic location information.

13. A network as claimed in any of claims 1 to 12, in which the mobile station used to determine said relative timings is a reference mobile station, and in which said reference mobile station includes calculation means adapted to calculate differences in bit and frame timing between transmissions from different base stations, using said relative timings, in combination with information concerning said reference mobile station's geographic location and said base stations' geographic locations, said calculated data being used to determine the RTDs (Real Time Differences) of the base stations and thereby the geographic location of a subscriber mobile station.

14. A network as claimed in claim 13, in which said reference mobile station includes means adapted to determine, and predict, a rate of change of said timing differences between base stations.

15. A network as claimed in claim 14, in which said reference mobile station includes transmission means for transmitting said calculated relative timings and rates of change to an external system for use in geographic position determination.

16. A network as claimed in claim 15, in which said transmission means are adapted to transmit base station position information to said external system.

17. A network as claimed in any of claims 1 to 16, in which said reference mobile station has a known fixed geographic location in the network.

18. A network as claimed in any of claims 1 to 16, in which the geographic location of said reference mobile station in the network is variable but determinable at any instant in time.

19. A network as claimed in claim 18, in which the geographic location of said reference mobile station in the network is determined by GPS.

20. A network as claimed in any of claims 1 to 19, in which at least some of said base stations each have a reference mobile station integral therewith.

21. A location system including a digital cellular radio communication network as claimed in any of the preceding claims.

22. A location system as claimed in claim 21, in which said system includes a control centre for controlling operation of the system.

23. A location system as claimed in claim 22, adapted to determine the geographic location of any one of said mobile stations (MSs) in said network, in which said relative timings of base stations (BSs) used to determine said geographic locations are subject to variations at a rate approaching that of a signalling frame rate of signals transmitted by said base stations, in which said system includes a reference mobile station for each set of base stations used to determine said geographic locations, in which a mobile station, whose location is to be determined (herein referred to as a 'target mobile station'), is assigned a set of base stations by said control centre, said target mobile station being adapted to measure relative timings of signals transmitted by said assigned set of base stations, at times given in terms of the frame number at an agreed base station, in which at least one reference mobile station, associated with said assigned set of base stations, is adapted to measure relative timings of said signals transmitted by said assigned set of base stations, in which said target mobile station

and said reference mobile station are adapted to transmit said measured timings to said control centre, in which said control centre is adapted to compare said time information from said target mobile station and said reference mobile station to determine a time difference, and in which said control centre is adapted to calculate the geographic location of said target mobile station using said time difference information, known to said control centre, concerning the geographic locations of said assigned set of base stations and said reference mobile station, said calculation being effected using conventional hyperbolic geometry equations.

24. A location system as claimed in claim 20, in which said control centre is adapted to change the set of base stations, assigned to a mobile station, as said mobile station travels within the coverage area of the digital cellular radio communication network.

25. A location system as claimed in claim 23 or claim 24, in which said control centre is adapted to co-ordinate information concerning timing measurements from at least some of said reference mobile stations.

26. A location system as claimed in any of claims 23 to 25, in which said system is adapted to track a fleet of vehicles, each one of which includes a mobile station (MS).

27. A vehicle navigation system adapted to enable vehicles to determine their geographic locations, in which said navigation system includes a location system as claimed in claim 22, and in which each of said vehicles includes a target mobile station.

28. A vehicle navigation system as claimed in claim 27, in which said system includes a reference mobile station for each set of base stations used to determine said geographic locations, in which rates of change of relative timings between base stations are sufficiently stable to enable said relative timings to be accurately predicted, for relatively long periods of time, according to a model shared between said reference and target mobile stations, in which said control centre is adapted to collect relative timing information and rate of change information measured by each of said reference mobile stations for respective sets of base stations, in which said control centre is adapted to distribute measurement information collected from said reference mobile stations to target mobile stations, travelling within the coverage area of said digital cellular radio communication network, said information distribution being such that each

of said target mobile stations has sufficiently accurate information concerning relative timings of base stations with which it can communicate in any given geographic location of said network; in which a target mobile station is adapted to measure relative timings of signals transmitted by a set of base stations in its current location, and to determine its geographic location using said measurements, together with said information distributed by said control centre and information concerning geographic locations of said set of base stations.

29. A vehicle navigation system as claimed in claim 28, in which said control centre is adapted to provide, to said target mobile station, information concerning geographic locations of said set of base stations.

30. A vehicle navigation system as claimed in claim 28, in which said target mobile station includes a database in which said information concerning geographic locations of said set of base stations is stored.

31. A mobile digital cellular radio communication network terminal for use in a network or location system according to any of the preceding claims, the terminal including means for identifying and measuring the time of arrival of a signal broadcast by a base station (2,3), each broadcast signal received by said mobile station being a composite signal consisting of one or more copies of a signal transmitted by a respective base station, said copies being displaced in time relative to each other according to the relative lengths of the paths traversed by each copy between the respective base station and the mobile station, and said time of arrival being measured as the time of arrival of the earliest arriving copy forming said composite signal relative to an internal time base of said mobile station, and said means being arranged to determine the relative timings of signals broadcast by a number of base stations.

32. A terminal according to claim 31, including any of the features of a mobile station of a digital cellular radio communication network as defined in any of claims 1 to 30.

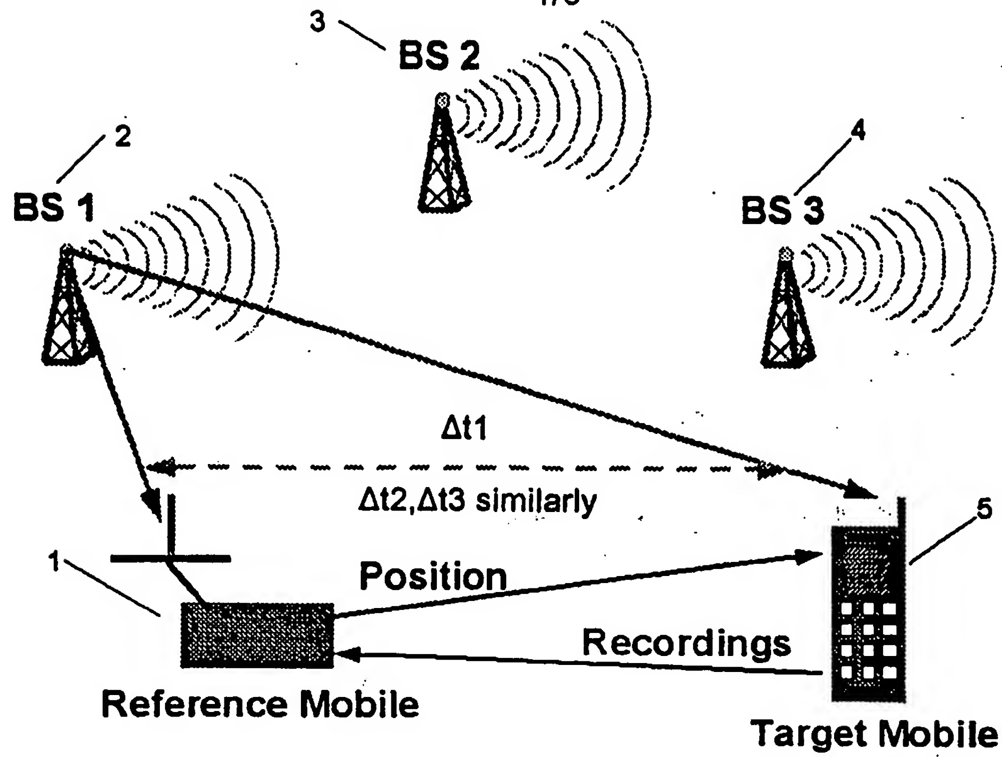


Figure 1

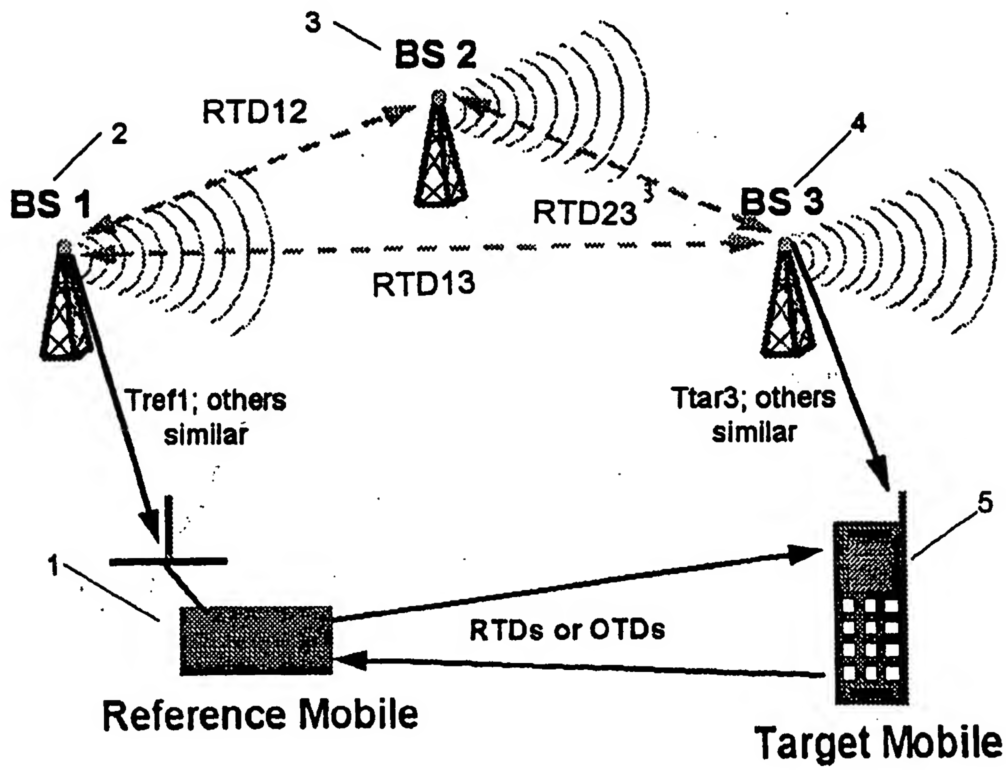


Figure 2

Figure 3A

Auto-correlation function for expected extended training sequence

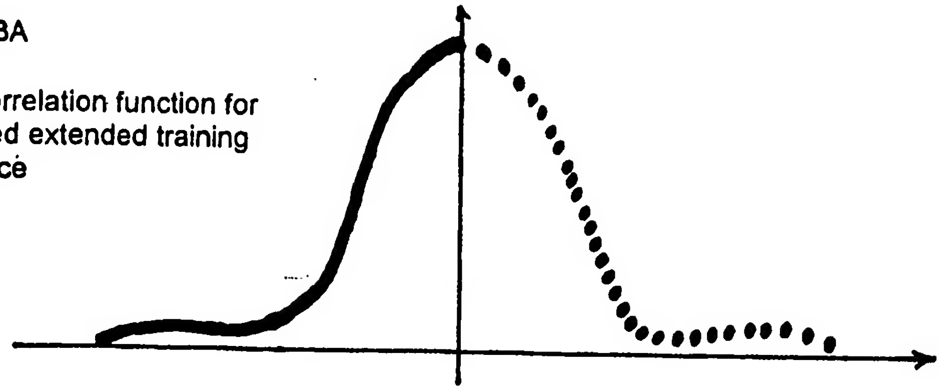


Figure 3B

Auto-correlation function for measured extended training sequence

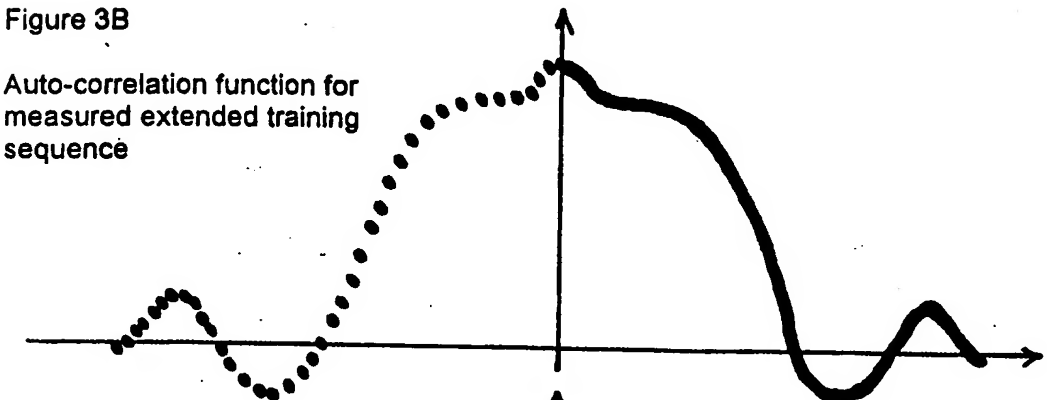


Figure 3C

Estimated cross-correlation function

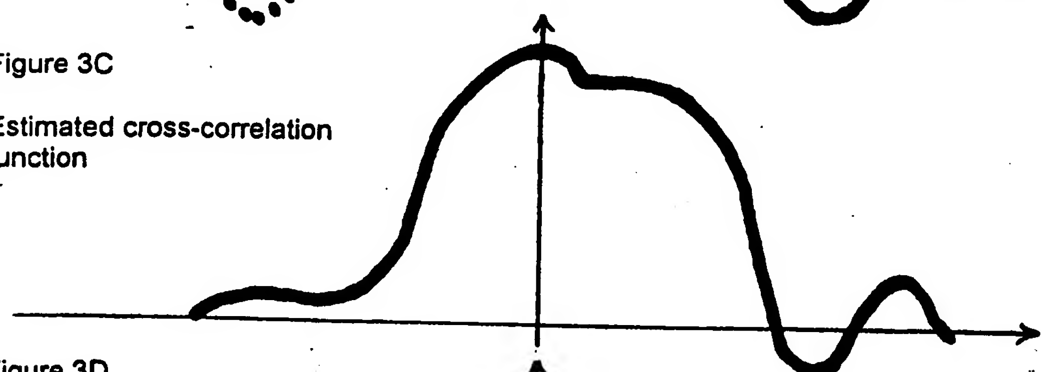
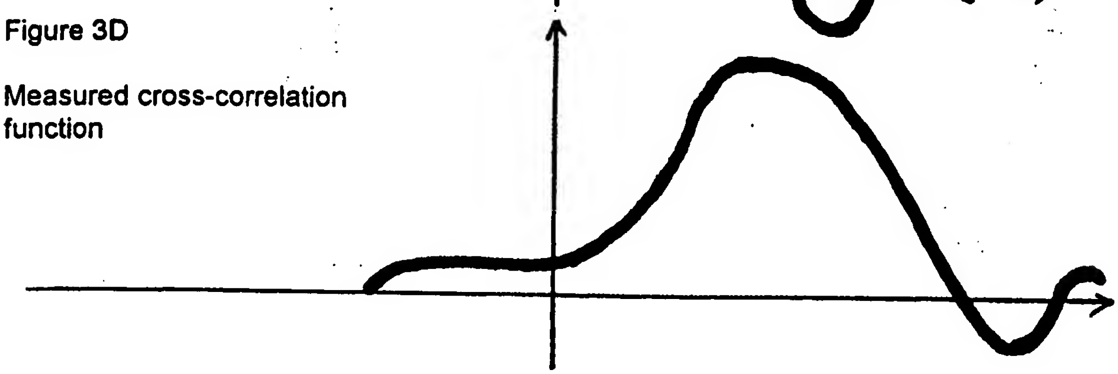


Figure 3D

Measured cross-correlation function



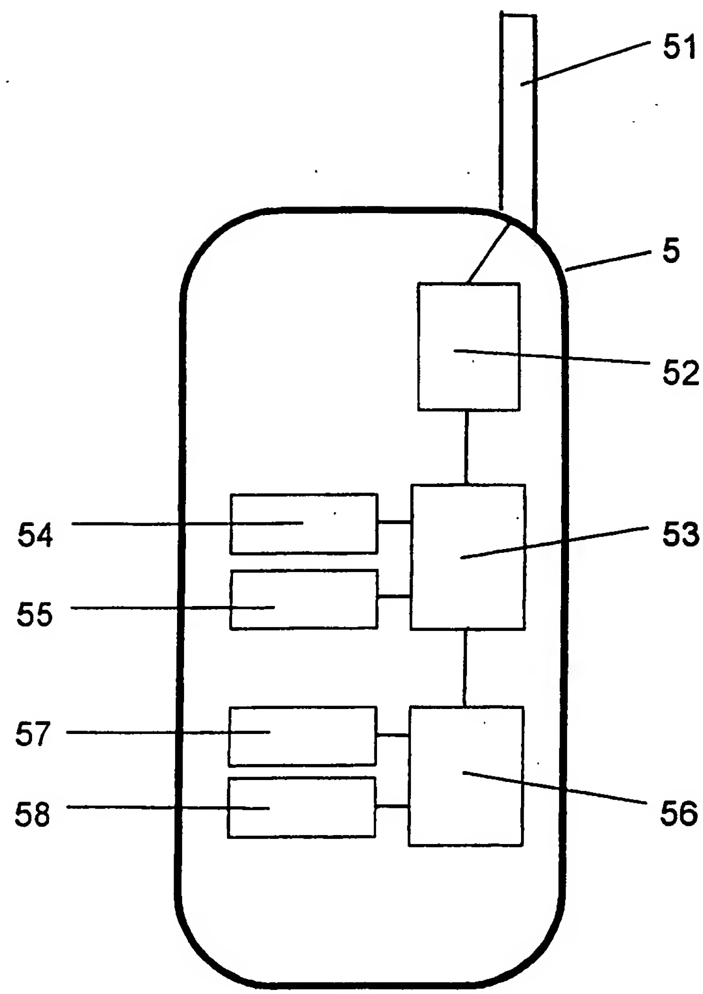


Figure 4

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 98/02538

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H04Q7/38

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H04Q G01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 97 23785 A (UNIVERSITY OF TECHNOLOGY,SYDNEY) 3 July 1997 cited in the application see abstract; figure 1	1
A	GB 2 260 050 A (NEC CORP.) 31 March 1993 see abstract; figure 1 see page 11, line 14 - page 12, line 7 see page 12, line 20 - line 23 see page 13, line 11 - line 15	1,17,24
A	US 5 293 645 A (SOOD) 8 March 1994 see abstract; claim 1; figure 1	1

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
28 October 1998	04/11/1998

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Danielidis, S

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/GB 98/02538

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9723785 A	03-07-1997	AU 1133297 A	17-07-1997
GB 2260050 A	31-03-1993	JP 5067996 A US 5423067 A	19-03-1993 06-06-1995
US 5293645 A	08-03-1994	JP 5211470 A	20-08-1993